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Atypical central auditory speech-sound discrimination in children who stutter as indexed by the mismatch negativity

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ABSTRACT

Purpose: Recent theoretical conceptualizations suggest that disfluencies in stuttering may arise from several factors, one of them being atypical auditory processing. The main purpose of the present study was to investigate whether speech sound encoding and central auditory discrimination, are affected in children who stutter (CWS).
Methods: Participants were 10 CWS, and 12 typically developing children with fluent speech (TDC). Event-related potentials (ERPs) for syllables and syllable changes [consonant, vowel, vowel-duration, frequency (F0), and intensity changes], critical in speech perception and language development of CWS were compared to those of TDC.
Results: There were no significant group differences in the amplitudes or latencies of the P1 or N2 responses elicited by the standard stimuli. However, the Mismatch Negativity (MMN) amplitude was significantly smaller in CWS than in TDC. For TDC all deviants of the linguistic multifeature paradigm elicited significant MMN amplitudes, comparable with the results found earlier with the same paradigm in 6-year-old children. In contrast, only the duration change elicited a significant MMN in CWS.
Conclusions: The results showed that central auditory speech-sound processing was typical at the level of sound encoding in CWS. In contrast, central speech-sound discrimination, as indexed by the MMN for multiple sound features (both phonetic and prosodic), was atypical in the group of CWS. Findings were linked to existing conceptualizations on stuttering etiology.

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Educational objectives: The reader will be able (a) to describe recent findings on central auditory speech-sound processing in individuals who stutter, (b) to describe the measurement of auditory reception and central auditory speech-sound discrimination, (c) to describe the findings of central auditory speech-sound discrimination, as indexed by the mismatch negativity (MMN), in children who stutter.

1. Introduction

Neural bases of stuttering have been intensively studied recently. The pathophysiology and neural bases underlying developmental stuttering, however, still remains poorly understood. Contemporary theories of stuttering incorporate many factors, like atypical neurophysiology, genetics, personality, linguistic factors, and atypical auditory processing (Bloodstein & Bernstein Ratner, 2008; Hall & Jerger, 1978; Liotti et al., 2010). We focus in this study on central speech-sound processing since accuracy of this function is essential for speech acquisition, production, and comprehension (Jansson-Verkasalo et al., 2003, 2010; Kuhl & Rivera-Gaziola, 2008).

Auditory processing difficulties may be subtle in nature in individuals with stuttering, and therefore may not manifest themselves in standardized behavioral tests (Kaganovich, Wray, & Weber-Fox, 2010). Auditory event-related potentials (ERPs) provide the necessary temporal and spatial resolution to detect subtle differences in auditory processing, and can be used to investigate well-defined stages of central auditory processing. Auditory ERPs are minute and discrete electrical potentials in the electroencephalogram (EEG) and are manifestations of neural activity that is specifically related, or time-locked, to sensory stimulation (Stapells & Kurzberg, 1991). The ERP waveform consists of a sequence of positive (P) and negative (N) deflections or peaks that are named according to their polarity and latency (timing relative to the stimulus onset), their serial order or cognitive meaning (Näätänen, 1992). Early components of the auditory ERPs reflect the neural correlates of reception and encoding of a stimulus. A P1-N1b-P2-N2 complex is typical in adults, P1 having a latency of about 50 ms (Ponton, Eggermont, Kwong, & Don, 2000). In children, however, the early stages of sound-feature encoding are reflected by obligatory P1-N2-N4 responses (Choudhury & Benasich, 2011). The P1 response latency decreases rapidly during the first decade of life from about 200–80 ms (Sharma, Dorman, & Spahr, 2002). P1 is followed by a broad negativity, N2, at about 200 ms (Čeponienė et al., 2001; Čeponienė, Rinne, & Näätänen, 2002; Niemitalo-Haapola et al., 2013). N1b is elicited in children only with long interstimulus intervals (Čeponienė et al., 2002) and becomes progressively consistent from the age of ten years onwards (Ponton, Eggermont, Khosla, Kwong, & Don, 2002). The language-related, negative-going N400 wave is an index of lexical access and integration (for review, see Kutas & Federmeier, 2011, for review), while the positive P600 is linked to the processing of syntactic violations (Friederici, 2002) or difficulty of syntactic integrations (Kaan, Harris, Gibson, & Holcomb, 2000). The magnitude (amplitude), speed (latency) and the location of processing reflect the efficacy of neural functions.

Central auditory discrimination can be investigated with the Mismatch Negativity (MMN) component of the auditory ERPs (Näätänen, 1992; Näätänen, Kujala, & Winkler, 2011). MMN is elicited even in inattentive subjects by potentially discriminable deviances in repetitive aspects of auditory stimuli (Näätänen, 1992; Winkler, 2007), and its latency and amplitude correlate with behavioral discrimination accuracy (Kujala & Näätänen, 2010; Kujala et al., 2001; Tiitinen, May, Reinikainen, & Näätänen, 1994).

Neuroanatomical (Beal, Gracco, Lafaille, & De Nil, 2007; Watkins, Smith, Davis, & Howell, 2008), as well as neurophysiological methods (Corbera, Corral, Escera, & Idiazábal, 2005; De Nil, Kroll, & Houle, 2001; De Nil et al., 2008; Hampton & Weber-Fox, 2008; Liotti et al., 2010) have been used to study auditory processing in adults who stutter. ERP studies (Corbera et al., 2005; Hampton & Weber-Fox, 2008; Liotti et al., 2010) have shown that auditory processing in adults who stutter is atypical in response to speech stimuli (Liotti et al., 2010) and in response to tones (Weber-Fox & Hampton, 2008) when compared to the controls. Similarly, a number of brain imaging studies have shown reduced (Chang, Kenney, Loucks, & Ludlow, 2009; De Nil et al., 2008; Fox et al., 2000; Ingham, Fox, Ingham, & Zamarripa, 2000) or increased activation (De Nil, Kroll, Kapur, & Houle, 2000; Kell et al., 2009; Neumann et al., 2003) in auditory areas in adults who stutter when compared to fluent speakers during a variety of speech tasks suggesting altered auditory processing. It has also been found that fluency-inducing therapies increase temporal activations (Fox et al., 1996; Neumann et al., 2003) which further support the assumption that temporal regions are part of a cortical–subcortical system. This suggestion is also corroborated by the study of Chang et al. (2009). Chang et al. (2009) investigated adults who stutter using fMRI during speech and non-speech perception, speech planning, and fluent production without masking. They found that adults who stutter had less activation in the frontal and temporoparietal regions relative to the controls during both speech and non-speech perception and planning. During speech and non-speech production, adults who stutter had less activation than the controls in the left superior temporal gyrus and the left pre-motor areas but greater activation in the right superior temporal gyrus, bilateral Heschl's gyrus, insula, putamen, and precentral motor regions. In addition, hemispheric differences in auditory processing have been reported in a number of studies between individuals who stutter and fluently speaking controls (Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Lu et al., 2010). While the precise nature of these differences is not clear, earlier suggestions that they may be related to atypical auditory inhibition, have not been confirmed (Beal, 2010; Beal et al., 2011). In a

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recent magnetoencephalography (MEG) study, Kikuchi et al. (2011) and Kikuchi, Umezaki, and Komune (2013) have offered an alternative hypothesis, linking the reduced auditory activation (suppression of P50, which is a magnetoencephalographic correlate of P1) to deficient sensory gating in the left hemisphere, accompanied by compensatory restructuring in the right hemisphere. However, most of these studies have been done with adults. In order to evaluate the extent to which atypical auditory processing contributes to the development of stuttering, auditory processing should be investigated in children closer to the onset of stuttering.

To the best of our knowledge, only a few studies have examined the neural correlates of stuttering in children (Beal et al., 2011; Beal, 2010; Chang et al., 2008; Kaganovich et al., 2010; Sato et al., 2011; Weber-Fox et al., 2008; Weber-Fox, Spruill, Spencer, & Smith, 2008; Weber-Fox, Hampton Wray, & Arnold, 2013). Neuroanatomical studies conducted by Chang et al. (2008) and Beal (2010) showed reduced gray matter volume in children who stutter (CWS) in the left inferior frontal gyrus, and in temporal regions, compared to typically developing children with fluent speech. Beal et al. (2011) used MEG to investigate auditory processing and speech-induced suppression during active vowel production relative to passive listening to their pre-recorded vowel productions. They reported that M50 had a longer left-hemisphere latency in CWS than in fluent children. Auditory ERPs were used by Kaganovich et al. (2010) to compare auditory processing and working memory in CWS and typically developing children. Children were presented with frequent 1 kHz tones interspersed with rare 2 kHz tones. The two groups did not differ on any measure of the P1 and N1 components, indicating that early auditory processing of pure tones is unimpaired in CWS. Weber-Fox et al. (2013) used ERPs to investigate semantic and syntactic processing of sentences with no overt speech in pre-school CWS. They found that the latency of the N400, an index of lexical access and integrations, was longer in CWS than in the controls. For syntactic processing, as indexed by the P600, the CWS exhibited notably different hemispheric distributions compared to the controls in response to syntactic violations. The increase in response to syntactic violation for P600 amplitude was more robust over the right than left hemisphere in CWS. In contrast, in TDC, the P600 amplitude was larger over the left than right hemisphere. To summarize, the pattern of these results has systematically shown that speech perception in these individuals is atypical.

Studies on central auditory discrimination in CWS are sparse. Kaganovich et al. (2010) found no significant group difference in central auditory discrimination in response to tone changes, as indexed by the MMN. Auditory discrimination difficulties, however, might be related specifically to speech or other complex sounds. The main aim of our study was to investigate whether a group of school-aged CWS differ from that of TDC in speech-sound encoding and central auditory discrimination of speech-syllables. Our hypothesis was that children with CWS have atypical MMNs reflecting inaccurate speech-sound discrimination. This hypothesis is based on earlier findings of reduced activation in auditory areas in adults (Chang et al., 2009; De Nil et al., 2008) and children (Weber-Fox et al., 2013) who stutter, atypical functional lateralization of speech processing (Sato et al., 2011), and behavioral tests showing diminished speech discrimination ability in children who stutter (Neef et al., 2012). Auditory ERPs in response to speech stimuli with variations in vowel, consonant, duration, pitch and intensity were used to determine whether CWS differ from TDC at the early level of central speech-sound processing and discrimination.

2. Method

2.1. Participants

Participants were 10 children (CWS; all boys; all right-handed) diagnosed with developmental stuttering and 12 typically developing non-stuttering children (TDC; 7 boys and 5 girls; one left-handed) matched for age. The mean age for the CWS was 7.07 years (SD = 1.26 years; range = 6.00–9.10 years) and 8.01 years (SD = .76; range = 7.11–9.08 years) for the TDC. There was no significant difference in age between the groups (p = .620; Mann–Whitney U-test). All participants were monolingual speakers of Finnish who were attending the regular school system. According to parental questionnaires, all children were healthy with no neurological, cognitive, speech, language, and/or learning deficits other than atypical speech disfluencies in the stuttering group. All participants successfully passed a hearing screening for normal hearing (tone-audiometry, SA 50, Entomed, Sweden). Since there were no standardized tests for school-aged children to assess morphology and syntax in the Finnish language at the time of measurements, language production was assessed by a qualified speech and language therapist based on the spontaneous speech samples, and was found to be within normal range.

Two subtests of the Wechsler Intelligence Scale for Children-Third Edition (WISC-III; Wechsler, 1991), Vocabulary and Block Design, were administered. In the Vocabulary subtest a child is asked to define provided words. Block Design is a subtest of perceptual reasoning. The child is asked to put together red-and-white blocks in a pattern according to a displayed model. Both subtests correlate highly with the WISC-III overall score (Groth-Marnat, 2009). The mean scores for the Vocabulary subtests were 9 for the CWS (SD 2.8; range 5–13) and 11 (SD 2.1; range 8–15) for the TDC. On the Block Design subtest, the CWS scored on average 10 (SD 4.0; range 5–15) compared to 10 for the TDC (SD 4. 1; range 4–16). No significant between-group differences were found for either Vocabulary (p = .05; Mann–Whitney U test) or Block Design (p = .921; Mann–Whitney U-test].

Spontaneous speech samples of all participants were collected and videotaped during the assessment. Speech fluency was assessed based on the video recordings by a qualified speech and language therapist using the Stuttering Severity Instrument for Children and Adults (SSI-3; Riley, 1994), and rated from no stuttering (value 0) to severe (value 4). Stuttering

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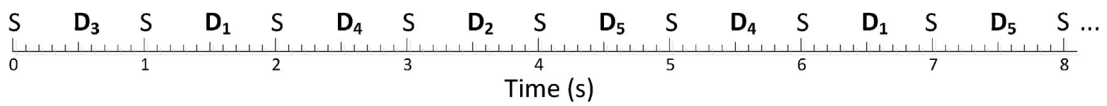

Fig. 1. Schematic illustration of the multi-feature paradigm. S denotes the standard stimulus, D1–D5 deviant stimuli. D1 was a vowel deviant, D2 a vowel duration deviant. D3–D5 were consonant, frequency and intensity deviants, respectively.

was determined to be very mild in two, mild in four, moderate in two and severe in two children. All TDC scored below 6 on the SSI-3.

The children gave verbal assent and the parents gave written informed consent prior to the experiments. The study was approved by the ethical committee of Oulu University Hospital.

2.2. Stimuli

A multi-feature paradigm with speech syllables was used to measure MMN as described by Lovio et al. (2009). In the multi-feature paradigm, the standard stimulus alternated with five different deviant stimuli (Fig. 1). The stimuli were 170 ms in duration, except for the duration deviant, which was 100 ms long. The fundamental frequency (F0) was 101 Hz. The standard stimulus was the syllable/te:/in 2 of the blocks, and/pi:/in the 2 other blocks. Third block of either/te:/or/pi:/as standards was presented in case the EEG data was noisy during the measurement or the presentation of the stimuli had to be stopped for some reason. With the syllable/te:/as the standard, the deviant parameters were (1) consonant change/t/to/p/resulting in/pe:/; (2) vowel change/e/to/i/resulting in/ti:/; (3) vowel duration change from 170 ms to 100 ms; (4) fundamental frequency change of F0 ±8% corresponding to F0 = 93 Hz and F0 = 108 Hz; 5) intensity change ±7 dB. With the syllable/pi:/as a standard, the consonant deviant was/t/(the syllable being/ti:/); vowel deviant/e/(the syllable being/pe:/). The rest of the changes were similar to those in the block with/te:/as a standard. There were 465 stimuli in a block. Each block of test stimuli started with 5 standard stimuli. Stimuli were binaurally presented through headphones with a 75 dB HL, and with a stimulus onset asynchrony (SOA) of 500 ms. The final data set consisted of an average of 211 (SD 59) accepted deviants for the TDC, and 182 (SD 47) for the CWS. There was no significant difference between the groups in the number of accepted deviants ($p = .06$).

2.3. EEG recording and analysis

The EEG was recorded with an electrocap with 19 electrodes embedded, using the NeuroScan Synamps amplifier, and NeuroScan 4.2 software (on-line bandpass 0.05–70 Hz, sampling rate 1000 Hz) (for a detailed overview of EEG-recording and analysis, see Luck, 2005). Electro-ocular activity (EOG) was recorded with two electrodes attached below the outer cantus of the left eye, and above the outer cantus of the right eye in accordance with clinical measurements done in the laboratory. During the data acquisition, the common reference was FCz, and after averaging, the data were re-referenced offline to linked mastoids.

The ERPs were digitally filtered off-line with a 1–30 Hz bandpass filter. The averaging was done for segmented and baseline corrected epochs (from −100 to 0 ms prestimulus for baseline correction, and 600 ms after the stimulus onset) by combining ERPs for the standard stimuli/te:/and/pi:/, and in a same way clustering the ERPs for the frequency, intensity, vowel, consonant, and vowel duration deviants separately. The epochs contaminated by artifacts exceeding ±125 μV at any electrode were omitted from the averaging procedure. The P1 and N2 peaks were identified from the waveforms for the standard stimuli. The P1 occurred within the time window of 80–170 ms and the N2 within the 150–260 ms window. (Table 1). The MMN was obtained by subtracting the standard-stimulus ERP from the deviant-stimulus ERP. The grand-mean peak MMN latencies were identified from the difference waveforms at F4 at 160–300 ms from the deviant-stimulus onset separately for each group and deviants (Table 1). The F4 electrode was chosen as the representative electrode because MMN was most visible in the grand-average waveform at electrode F4 for both groups and for different deviants. Furthermore, previous studies have shown that the MMN is maximal over the fronto-central areas of the scalp, particularly at Fz, F3, and F4 (Kujala, Tervaniemi, & Schröger, 2007). The mean amplitudes were measured from the difference waves of each subject with

Table 1
The time windows for the peak detection of the P1, N2, and MMN in response to different deviants in children who stutter and in fluently speaking controls.

Stimuli	Children with stuttering	Controls
Standard	P1 80–170 ms N2 150–260 ms	P1 80–170 ms N2 150–260 ms
	MMN	MMN
Consonant change	210–310 ms	220–320 ms
Vowel change	160–260 ms	160–260 ms
Vowel duration change	200–300 ms	200–300 ms
Intensity change	190–290 ms	170–270 ms
Frequency change	200–300 ms	170–270 ms

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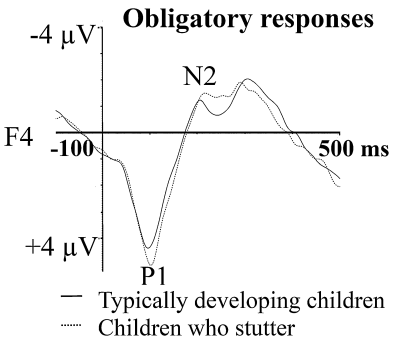

Fig. 2. The grand mean ERPs for the standard sound at the F4 electrode in children who stutter and in typically developing children.

a 50-ms window centered around the most negative peak (±25 ms). A two-tailed *t*-test was used to investigate, whether the MMN responses differed significantly from zero at F4.

The amplitude and latency differences in ERPs were first tested at 9 electrodes by using four-way repeated-measures ANOVAs of the SPSS statistical program with Group (CWS,TDC), as a between-subject factor and Deviant type (consonant, vowel, vowel duration, frequency, intensity), Hemisphere [Right (F4, C4, P4) × Midline (Fz, Cz, Pz) × Left (F3, C3, P3)] × Anterior–Posterior [Frontal (F3, Fz, F4) × Central (C3, Cz, C4) × Parietal (P3, Pz, P4)] as within-subject factors. Consistent with our hypothesis and based on visual inspection, the grand average ERP waveform showed reduced MMN amplitudes in response to all deviants in CWS when compared to the TDC. Therefore, separate SPSS analyses were done by using the three-way repeated-measures ANOVAs of the SPSS statistical program with Group (CWS,TDC), as a between-subject factor and Hemisphere [Right (F4, C4, P4) × Midline (Fz, Cz, Pz) × Left (F3, C3, P3)] × Anterior–Posterior [Frontal (F3, Fz, F4) × Central (C3, Cz, C4) × Parietal (P3, Pz, P4)] as within-subject factors. Two sample *t*-tests were used to examine significant interactions and partial eta squared (η_p^2) for the effect size estimation. The Huynh–Feldt correction was applied when appropriate, and corrected degrees of freedom are reported. The correlations between the stuttering severity rating and MMN amplitudes were tested using the Pearson correlation coefficients. MMN amplitudes used in the analyses were mean values of the right, left, midline, frontal, central, parietal electrodes for each subject.

2.4. Procedure

Participants were tested during two separate visits to the clinic for approximately a total test duration of 90 min. All tests were conducted by the first author, a qualified speech-language therapist. During the first visit participants were administered the tone audiometry, EEG-recording, and the first spontaneous speech sample was also collected. During the EEG recording, the child sat comfortably in an electrically shielded chamber. He/she was instructed to ignore the stimuli during the recording, and to watch the silent, self-chosen cartoon on a video display. There was one short break during the recording to keep the child alert. During the second visit the WISC-III subtests and the second speech sample were collected.

3. Results

3.1. Standard-sound ERPs

A prominent P1 followed by the N2 response was elicited in both groups (Fig. 2). The amplitude of the P1 over 9 electrodes was 3.2 μV in CWS, and 3.3 μV in TDC (Table 2). The latency of the P1 over 9 electrodes was 106 ms in CWS and 101 ms in TDC. The N2 amplitude over 9 electrodes was −1.2 μV in CWS, and −1.1 μV in TDC, the N2 latency being 212 ms and 211 ms, respectively. No significant differences were found between the two subject groups in either the P1 or N2 amplitudes or latencies.

Table 2
Amplitudes and latencies of P1 and N2 in children who stutter (CWS) and in typically developing children (TDC). No significant differences between the groups were found either in the latencies or amplitudes.

Electrodes	P1				N2			
	Amplitude (μV)		Latency (ms)		Amplitude (μV)		Latency (ms)	
	CWS	TDC	CWS	TDC	CWS	TDC	CWS	TDC
Over 9 electrodes	3.2	3.3	106	101	−1.2	−1.1	212	211
Left array	3.2	3.4	104	99	−1.4	−1.3	210	214
Right array	3.1	3.2	106	103	−1.2	−0.90	211	210

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Table 3
MMN mean amplitudes (μV) and latencies (ms) at electrode F4 in children who stutter and in fluently speaking children. The latencies (ms) are defined from the grand mean average in response to consonant, vowel, frequency and intensity change in CWS because those responses could not be defined reliably from each subject. Therefore, standard deviations cannot be reported for these latencies.

Deviant	Children who stutter		Fluently speaking children	
	Amplitude (μV)	Latency (ms)	Amplitude (μV)	Latency (ms)
Consonant	−0.4 (1.9)	270	−1.2 (1.1)	267 (30)
Vowel	−1.2 (1.9)	210	−2.1 (1.3)	220 (26)
Vowel-duration	−1.9 (1.2)	244 (14)	−2.5 (1.6)	240 (15)
Frequency	−0.87 (1.8)	220	−1.6 (1.5)	233 (21)
Intensity	−0.44 (0.7)	220	−1.1 (1.0)	236 (23)

Standard deviation in brackets.

3.2. MMN amplitude

In TDC, all deviant stimuli elicited MMN amplitudes that significantly differed from zero ($p = .000–.004$) indicating that majority of the controls had the MMN for all deviants. For the CWS, in contrast, the MMN amplitude significantly differed from zero only in response to duration change ($p = .001$). The four-way repeated-measures ANOVAs of the SPSS statistical program with Group (CWS,TDC), as a between-subject factor and Deviant type (consonant, vowel, vowel duration, frequency, intensity), Hemisphere [Right (F4, C4, P4) × Midline (Fz, Cz, Pz) × Left (F3, C3, P3)] × Anterior–Posterior [Frontal (F3, Fz, F4) × Central (C3, Cz, C4) × Parietal (P3, Pz, P4)] as within-subject factors showed that there was no significant difference between the groups. However, the three-way repeated-measures ANOVAs with Group (CWS,TDC), as a between-subject factor and Hemisphere [Right (F4, C4, P4) × Midline (Fz, Cz, Pz) × Left (F3, C3, P3)] × Anterior–Posterior [Frontal (F3, Fz, F4) × Central (C3, Cz, C4) × Parietal (P3, Pz, P4)] as within-subject factors revealed that the MMN amplitude was significantly smaller in CWS than in TDC [$F(12,68) = 6.338$, $p = .013$; $\eta_p^2 = 0.55$, observed power = 0.7, Tables 3 and 4; Figs. 3 and 4]. In addition, the three-way repeated-measures ANOVAs showed a significant Group × Right–Left × Anterior–Posterior interaction [$F(3.6; 394) = 5.046$, $p = .001$; $\eta_p^2 = 0.45$, observed power = 1.0] which was due to significantly smaller MMN amplitudes frontally ($p = .008$) and parietally ($p = .023$) in CWS than in TDC. Furthermore, the MMN amplitudes were smaller in the right ($p = .002$) and left ($p = .010$) hemisphere as well as at midline Fz, but not in Cz and Pz.

A correlation between the MMN amplitude and stuttering severity was tested to investigate whether central auditory speech-sound discrimination varied with stuttering severity. The results showed that there was a significant correlation between the MMN amplitude over the mean of the central electrodes (C3, Cz, C4) and stuttering severity ($R = .328$; $p = .020$). No significant correlations were found between the stuttering severity and MMN amplitude over the right (F4, C4, P4), left (F3, C3, P3), midline (Fz, Cz, Pz), Frontal (F3, Fz, F4) or parietal (P3, Pz, P4) electrodes.

Table 4
The MMN mean amplitude for each child at electrode F4 which was used to test the significance of the MMN.

Child	Group	Consonant change	Vowel change	Vowel duration change	Frequency change	Intensity change
1	TDC	−1.5	−4.2	−3.4	−2.4	−1.5
2	TDC	+0.6	+0.7	−1.1	+1.7	+0.6
3	TDC	+0.4	−2.1	−2.9	−3.2	−0.3
4	TDC	−1.2	−1.8	−0.2	−1.2	−1.0
5	TDC	−0.3	−1.1	−0.0	−1.4	−0.2
6	TDC	−1.1	−1.7	−3.2	−0.7	−0.8
7	TDC	−2.1	−4.2	−5.8	−4.4	−2.4
8	TDC	−1.3	−2.7	−2.6	−2.0	−1.1
9	TDC	−1.9	−1.7	−3.0	−2.4	−1.4
10	TDC	−1.4	−2.9	−1.9	−0.6	−1.3
11	TDC	−3.6	−2.4	−3.6	−2.2	−3.4
12	TDC	−1.4	−1.5	−2.7	−0.8	−1.0
13	CWS	−0.1	−2.1	−1.8	−1.6	−0.8
14	CWS	−0.4	+0.2	−2.0	−0.7	−0.6
15	CWS	−2.1	−4.3	−3.3	−2.0	+0.1
16	CWS	−0.5	−1.6	−1.0	+0.3	−0.9
17	CWS	+4.6	+2.9	−0.1	+2.6	+0.9
18	CWS	−1.6	−1.6	−2.0	+0.5	−0.5
19	CWS	+0.2	−1.5	−1.6	−0.3	−1.1
20	CWS	−1.8	−1.5	−0.7	−2.9	+0.5
21	CWS	−0.8	−0.2	−2.9	−0.9	−1.1
22	CWS	−1.5	−2.8	−3.9	−3.7	−0.8

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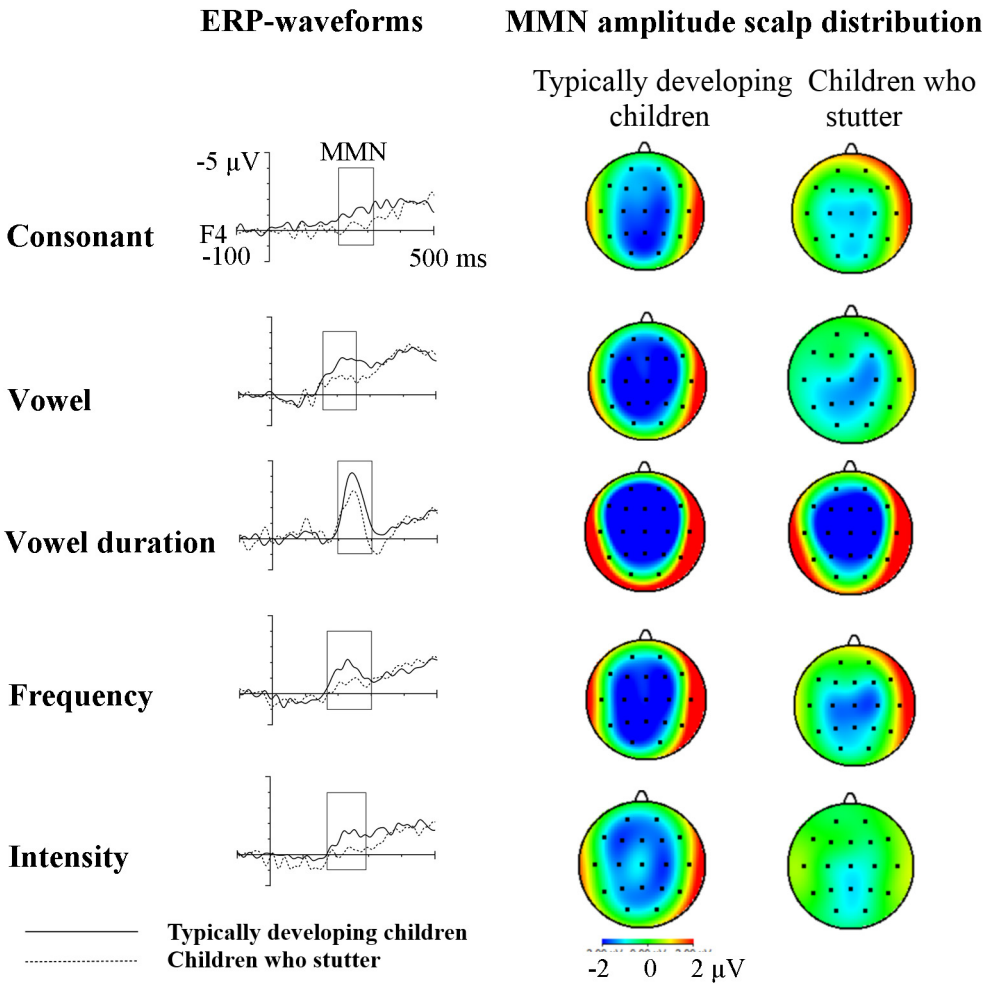

Fig. 3. Deviant-minus-standard difference waveform at F4 for changes in consonant, vowel, vowel duration, frequency and intensity in children who stutter and in typically developing children. The MMN amplitude scalp distribution in the time window of the MMN in children who stutter (on the right) and in typically developing children (on the left).

3.3. MMN latency

The MMN latency was compared between the two groups only for the duration change since it was the only deviant that significantly differed from zero in CWS. The three-way ANOVA with Group as a between-subject factor and Hemisphere [Right (F4, C4, P4) × Midline (Fz, Cz, Pz) × Left (F3, C3, P3)] × Anterior–Posterior [Frontal (F3, Fz, F4) × Central (C3, Cz, C4) × Parietal

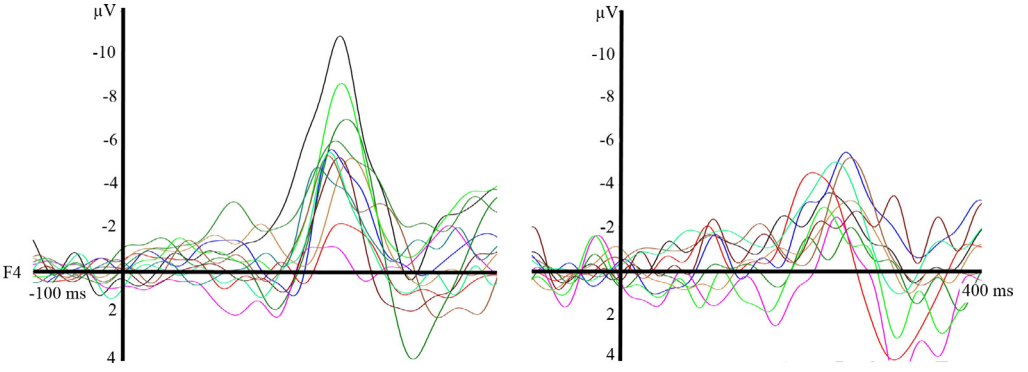

Fig. 4. Deviant-minus-standard difference waveform at F4 for changes in vowel duration in individual children who stutter (on the right) and in typically developing children (on the left).

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(P3, Pz, P4)] as within-subject factors showed that there was no significant group difference for this MMN latency in response to duration change. No significant correlations were found between the MMN latency and stuttering severity.

4. Discussion

Because it has been hypothesized that atypical auditory processing may influence the occurrence of stuttering (Hall & Jerger, 1978; Liotti et al., 2010), the current study focused on investigating auditory speech-sound processing in CWS using both responses to standard sounds and the MMN component of auditory ERPs. Our results suggest atypical cortical speech sound discrimination but normal-like sound encoding in CWS. We found that the P1 and N2 elicited by standard sounds were similar in CWS and in TDC. As such, our results corroborate the earlier findings of Kaganovich et al. (2010), who used auditory P1 and N1, elicited by 1000 Hz and 2000 Hz tones. They found no significant differences between CWS and typically developing children in P1 or N1 for non-speech sounds suggesting normal sound encoding in CWS. Our results show that sound encoding in these children is typical also for speech sounds.

The magnitude and speed as well as the place of processing reflect the efficacy of neural functions (Tervaniemi & Hugdahl, 2003). Based on visual inspectation, the grand average ERP waveforms of the current study showed reduced MMN amplitudes in response to all deviants in CWS when compared to the TDC. However, no significant group differences were found for the deviant types. This may be due to the small MMN amplitudes in response to each deviant, rather small samples, and the inter-individual differences. However, when all the deviants were included in the same analysis, the MMN amplitudes were significantly smaller for speech sound changes over the left and right hemispheres in CWS compared to TDC, which suggests ineffective neural processing of speech sound differences (Tervaniemi & Hugdahl, 2003). TDC showed amplitudes that were comparable to those reported in earlier studies using the same or comparable linguistic multi-feature paradigm in 6-year-old (Lovio, Näätänen, & Kujala, 2010). In addition, the *t*-tests of MMNs against zero indicated that the majority of controls had an MMN for all deviants, whereas the majority of the CWS exhibited the MMN for the duration deviant only. Since the pre-attentive MMN is an index of auditory discrimination and auditory sensory memory (Kujala & Näätänen, 2010) the current results suggest that many CWS have widespread difficulties in central auditory speech-sound discrimination. This finding corroborates results obtained earlier with fMRI showing reduced activation in auditory areas bilaterally and atypical functional lateralization for speech processing in individuals with stuttering (Chang et al., 2009; De Nil et al., 2008). Furthermore, the results are in line with those of Neef et al. (2012) and Weber-Fox et al. (2013) indicating abnormally weak perceptual acuity for stop consonants in adults who stutter and atypical auditory semantic and syntactic processing of speech in CWS, respectively.

Our results are inconsistent with those of Kaganovich et al. (2010), who found no significant group differences between CWS and typically developing children in central auditory discrimination in response to tones. One explanation for these discrepant results might be the different kinds of stimuli used. Kaganovich et al. (2010) used sine tones with a quite pronounced acoustic difference whereas our stimuli were sound changes in syllables. Thus, it is possible that central auditory encoding and discrimination of tones is intact in CWS, whereas cortical discrimination of speech stimuli is atypical in children with stuttering. Accurate sound discrimination is a prerequisite for precise speech sound representations, speech perception, and speech production (Hickok, Houde, & Rong, 2011; Kuhl & Rivera-Gaziola, 2008). Therefore, stuttering severity might be associated with atypical speech sound discrimination.

A correlation analysis was carried out in the current study to investigate the relationship between stuttering severity and central auditory discrimination. The results showed a positive correlation between MMN amplitudes at central scalp locations and stuttering severity. In other words, more diminished MMN amplitudes, which usually indexes poorer speech-sound discrimination, were associated with more severe stuttering. Our results thus support the hypothesis of the influence of atypical auditory processing on stuttering (Hall & Jerger, 1978; Liotti et al., 2010).

Well-developed native language phoneme discrimination predicts good speech and language development (Jansson-Verkasalo et al., 2010; Kuhl & Rivera-Gaziola, 2008), while deficits in this ability have been linked to difficulties in language learning (Jansson-Verkasalo et al., 2010; Kuhl & Rivera-Gaziola, 2008), naming (Jansson-Verkasalo et al., 2003, 2004), and reading (Kujala et al., 2007), among other skills. The current results, as well as those reported by Cai et al. (2012) and Weber-Fox et al. (2013), might suggest that CWS have difficulties in receiving sufficient auditory support for speech production, an integrative process that normally occurs quickly, efficiently and seamlessly. While it is difficult to relate our ERP findings in children directly to reduced auditory activation observed in studies of adults with stuttering, and comparable fMRI studies in CWS are lacking, the fact that our data confirmed the presence of atypical auditory processing in younger CWS suggests that such an auditory difficulty may have a critical role very early during the development of stuttering.

The results of our study should be interpreted cautiously as they were observed in a relatively small sample of children. We found differences in group comparisons but the MMN is so far not a diagnostic tool at the individual level. However, the fact that even with such a small sample statistically significant group differences were observed indicates differences between the stuttering and non-stuttering children. While stuttering is a multi-factorial communication disorders, attention should also be paid to the possible presence of inter-individual differences in central speech-sound discrimination, central auditory discrimination of different speech features and their possible relationship with stuttering severity, recovery from stuttering, treatment outcome, and a number of other possible characteristics of developmental stuttering.

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In conclusion, our study showed group differences in central speech-sound discrimination between CWS and TDC using the multi-feature MMN paradigm involving several different deviant types. These results suggest that speech production system in CWS might be affected by less accurate representations of speech sounds.

CONTINUING EDUCATION

QUESTIONS

1. Early components of auditory event-related potentials (obligatory responses) reflect
(a) auditory discrimination
(b) auditory reception and encoding
(c) auditory sensory memory
(d) sustained attention
(e) semantic processing of words
2. Mismatch negativity (MMN) is an index of
(a) attention
(b) motor integration
(c) central auditory discrimination
(d) auditory localization
(e) negative attitude
3. Behavioral auditory discrimination accuracy has been shown to correlate with the
(a) P1 amplitude
(b) P1 latency
(c) MMN amplitude
(d) EEG amplitude
(e) EEG latency
4. The present study showed that
(a) sound encoding is typical in CWS
(b) sound encoding is atypical in children who stutter
(c) sound encoding cannot be measured in children
(d) sound encoding is better in CWS than in TDC
(e) sound encoding was not measured in this study
5. Central auditory discrimination
(a) was typical in CWS when compared to TDC
(b) was atypical in CWS when compared to TDC
(c) was too slow in CWS
(d) was too quick in CWS
(e) was enhanced in CWS

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